

METHOD OF MAKING A COATING OF A MICROTEXTURED SURFACE

FIELD OF THE INVENTION

5 This application is a continuation in part of Application Serial No. 09/212,780, filed December 16, 1998, entitled "Conformal Coating of a Microtextured Surface."

The present invention relates generally to a method of making plasma polymerized polymer films. More specifically, the present invention relates to making a plasma polymerized polymer film onto a microtextured surface via plasma enhanced chemical deposition with a flash evaporated feed source of a low vapor pressure compound.

As used herein, the term "(meth)acrylic" is defined as "acrylic or methacrylic." Also, (meth)acrylate is defined as "acrylate or methacrylate."

As used herein, the term "cryocondense" and forms thereof refer to the physical phenomenon of a phase change from a gas phase to a liquid phase upon the gas contacting a surface having a temperature lower than a dew point of the gas.

As used herein, the term "polymer precursor" includes monomers, oligomers, and resins, and combinations thereof. As used herein, the term "monomer" is defined as a molecule of simple structure and low molecular weight that is capable of combining with a number of like or unlike molecules to form a polymer. Examples include, but are not limited to, simple acrylate molecules, for example, hexanedioldiacrylate, or tetraethyleneglycoldiacrylate, styrene, methyl styrene, and combinations thereof. The molecular weight of monomers is generally less than 1000, while for fluorinated monomers, it is generally less than 2000. Substructures such as CH₃, t-butyl, and CN can also be included. Monomers may be combined to form oligomers and resins, but do not combine to form other monomers.

As used herein, the term "oligomer" is defined as a compound molecule of at least two monomers that can be cured by radiation, such as ultraviolet, electron beam, or x-ray, glow discharge ionization, and spontaneous thermally induced curing. Oligomers include low molecular weight resins. Low molecular weight is defined herein as about 1000 to about 20,000

exclusive of fluorinated monomers. Oligomers are usually liquid or easily liquifiable.

Oligomers do not combine to form monomers.

As used herein, the term "resin" is defined as a compound having a higher molecular weight (generally greater than 20,000) which is generally solid with no definite melting point.

5 Examples include, but are not limited to, polystyrene resin, epoxy polyamine resin, phenolic resin, and acrylic resin (for example, polymethylmethacrylate), and combinations thereof.

BACKGROUND OF THE INVENTION

10 The basic process of plasma enhanced chemical vapor deposition (PECVD) is described in THIN FILM PROCESSES, J.L. Vossen, W. Kern, editors, Academic Press, 1978, Part IV, Chapter IV - 1 Plasma Deposition of Inorganic Compounds, Chapter IV - 2 Glow Discharge Polymerization, herein incorporated by reference. Briefly, a glow discharge plasma is generated on an electrode that may be smooth or have pointed projections. Traditionally, a gas inlet introduces high vapor pressure monomeric gases into the plasma region wherein radicals are
15 formed so that upon subsequent collisions with the substrate, some of the radicals in the monomers chemically bond or cross link (cure) on the substrate. The high vapor pressure monomeric gases include gases of CH₄, SiH₄, C₂H₆, C₂H₂, or gases generated from high vapor pressure liquid, for example styrene (10 torr at 87.4°F (30.8°C)), hexane (100 torr at 60.4°F (15.8°C)), tetramethyldisiloxane (10 torr at 82.9°F (28.3°C)), 1,3-
20 dichlorotetramethyldisiloxane (75 torr at 44.6°F (7.0°C)), and combinations thereof that may be evaporated with mild controlled heating. Because these high vapor pressure monomeric gases do not readily cryocondense at ambient or elevated temperatures, deposition rates are low (a few tenths of micrometer/min maximum) relying on radicals chemically bonding to the surface of interest instead of cryocondensation. Remission due to etching of the surface of interest by the
25 plasma competes with reactive deposition. Lower vapor pressure species have not been used in PECVD because heating the higher molecular weight monomers to a temperature sufficient to vaporize them generally causes a reaction prior to vaporization, or metering of the gas becomes difficult to control, either of which is inoperative.

The basic process of flash evaporation is described in U.S. Patent No. 4,954,371 herein incorporated by reference. This basic process may also be referred to as polymer multi-layer (PML) flash evaporation. Briefly, a radiation polymerizable and/or cross linkable material is supplied at a temperature below a decomposition temperature and polymerization temperature of the material. The material is atomized to droplets having a droplet size ranging from about 1 to about 50 microns. An ultrasonic atomizer is generally used. The droplets are then flash vaporized, under vacuum, by contact with a heated surface above the boiling point of the material, but below the temperature which would cause pyrolysis. The vapor is cryocondensed on a substrate then radiation polymerized or cross linked as a very thin polymer layer.

According to the state of the art of making plasma polymerized films, PECVD and flash evaporation or glow discharge plasma deposition and flash evaporation have not been used in combination. However, plasma treatment of a substrate using a glow discharge plasma generator with inorganic compounds has been used in combination with flash evaporation under a low pressure (vacuum) atmosphere, as reported in J.D. Affinito, M.E. Gross, C.A., Coronado, and P.M. Martin, "Vacuum Deposition Of Polymer Electrolytes On Flexible Substrates," Proceedings of the Ninth International Conference on Vacuum Web Coating, November 1995, ed. R. Bakish, Bakish Press 1995, pg. 20-36, and as shown in FIG. 1a. In that system, the plasma generator 100 is used to etch the surface 102 of a moving substrate 104 in preparation to receive the monomeric gaseous output from the flash evaporation 106 that cryocondenses on the etched surface 102 and is then passed by a first curing station (not shown), for example electron beam or ultra-violet radiation, to initiate cross linking and curing. The plasma generator 100 has a housing 108 with a gas inlet 110. The gas may be oxygen, nitrogen, water or an inert gas, for example argon, or combinations thereof. Internally, an electrode 112 that is smooth or having one or more pointed projections 114 produces a glow discharge and makes a plasma with the gas which etches the surface 102. The flash evaporator 106 has a housing 116, with a monomer inlet 118 and an atomizing nozzle 120, for example an ultrasonic atomizer. Flow through the nozzle 120 is atomized into particles or droplets 122 which strike the heated surface 124 whereupon the particles or droplets 122 are flash evaporated into a gas that flows past a series of baffles 126

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(optional) to an outlet 128 and cryocondenses on the surface 102. Although other gas flow distribution arrangements have been used, it has been found that the baffles 126 provide adequate gas flow distribution or uniformity while permitting ease of scaling up to large surfaces 102. A curing station (not shown) is located downstream of the flash evaporator 106. The monomer may be an acrylate (FIG. 1b).

These flash evaporation methods have traditionally been used on smooth surfaces or surfaces lacking microtextured features. A disadvantage of traditional PML (polymer multi-layer) flash evaporation methods is that during the time between condensation of the vapor to a liquid film and the radiation cross linking of the liquid film to a solid layer, the liquid tends to flow preferentially to low points and flatter regions because of gravity and surface tension (FIG. 2a) so that the coating surface 150 is geometrically different from the substrate surface 160. Reducing surface temperature can reduce the flow somewhat, but should the monomer freeze, then cross linking is adversely affected. Using higher viscosity monomers is unattractive because of the increased difficulty of degassing, stirring, and dispensing of the monomer.

Many devices have microtextured surfaces, for example, quasi-corner reflector type micro-retroreflectors, diffraction gratings, micro light pipes and/or wave guides, and microchannel flow circuits. The devices are presently made by spin coating or physical vapor deposition (PVD). Physical vapor deposition may be either evaporation or sputtering. With spin coating, surface area coverage is limited and scaling up to large surface areas requires multiple parallel units rather than a larger single unit. Moreover, physical vapor deposition processes are susceptible to pin holes.

Therefore, there is a need for a method for coating devices that have microtextured surfaces with a conformal coating.

SUMMARY OF THE INVENTION

The present invention is a method of conformally coating a microtextured surface. The method includes plasma polymerization wherein a polymer precursor is cured during plasma polymerization. The method is a combination of flash evaporation with plasma enhanced



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chemical vapor deposition (PECVD) that provides the unexpected improvements of conformally coating a microtextured substrate at a rate surprisingly faster than standard PECVD deposition rates.

5 The conformal coating material may be a polymer precursor, or a mixture of polymer precursor with particle materials. The polymer precursor, particle, or both may be conjugated, or unconjugated.

10 The method of the present invention includes flash evaporating a polymer precursor forming an evaporate, passing the evaporate to a glow discharge electrode creating a glow discharge polymer precursor plasma from the evaporate, and cryocondensing the glow discharge polymer precursor plasma on a microtextured surface as a condensate, and polymerizing the condensate before the condensate flows, thereby conformally coating the microtextured surface. The crosslinking results from radicals created in the glow discharge plasma.

15 Accordingly, the present invention provides a method of conformally coating a microtextured surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1a is a cross section of a prior art combination of a glow discharge plasma generator with inorganic compounds with flash evaporation.

FIG. 1b is a chemical diagram of a (meth-)acrylate molecule.

20 FIG. 2a is an illustration of a non-conformal coating (prior art).

FIG. 2b is an illustration of a conformal coating according to the method of the present invention.

FIG. 3 is a cross section of an apparatus which can be used in method of the present invention of combined flash evaporation and glow discharge plasma deposition.

25 FIG. 3a is a cross section end view of the apparatus of FIG. 3.

FIG. 4 is a cross section of an apparatus wherein the substrate is the electrode.

FIG. 5a is a chemical diagram including phenylacetylene.

FIG. 5b is a chemical diagram of triphenyl diamine derivative.

FIG. 5c is a chemical diagram of quinacridone.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is a method of conformally coating a microtextured surface.

5 Microtextured surfaces include but are not limited to quasi-corner reflector type micro-retroreflectors, diffraction gratings, microlight pipes and/or wave guides, microchannel flow circuits and combinations thereof. A conformal coating is illustrated in FIG. 2b wherein a coating surface 150 is geometrically similar to the microtextured surface 160. Conformally coating a microtextured surface may be done with the apparatus shown in FIG. 3. The method of the present invention may be performed within a low pressure (vacuum) environment or
10 chamber. Pressures typically range from about 10^{-1} torr to 10^{-6} torr, although they may be higher or lower. The flash evaporator 106 has a housing 116, with a polymer precursor inlet 118 and an atomizing nozzle 120. Flow through the nozzle 120 is atomized into particles or droplets 122 which strike the heated surface 124 whereupon the particles or droplets 122 are flash evaporated
15 into a gas or evaporate that flows past a series of baffles 126 to an evaporate outlet 128 and cryocondenses on the microtextured surface 102. Cryocondensation on the baffles 126 and other internal surfaces is prevented by heating the baffles 126 and other surfaces to a temperature in excess of a cryocondensation temperature or dew point of the evaporate. Although other gas flow distribution arrangements have been used, it has been found that the baffles 126 provide
20 adequate gas flow distribution or uniformity while permitting ease of scaling up to large microtextured surfaces 102. The evaporate outlet 128 directs gas toward a glow discharge electrode 204 creating a glow discharge plasma from the evaporate. In the embodiment shown in FIG. 3, the glow discharge electrode 204 is placed in a glow discharge housing 200 having an evaporate inlet 202 proximate the evaporate outlet 128. In this embodiment, the glow discharge
25 housing 200 and the glow discharge electrode 204 are maintained at a temperature above a dew point of the evaporate. The glow discharge plasma exits the glow discharge housing 200 and cryocondenses on the microtextured surface 102 of the microtextured substrate 104. It is

preferred that the microtextured substrate 104 is kept at a temperature below a dew point of the evaporate, preferably ambient temperature or cooled below ambient temperature to enhance the cryocondensation rate. In this embodiment, the microtextured substrate 104 is moving and may be electrically grounded, electrically floating, or electrically biased with an impressed voltage to draw charged species from the glow discharge plasma. If the microtextured substrate 104 is electrically biased, it may even replace the electrode 204 and be, itself, the electrode which creates the glow discharge plasma from the polymer precursor gas. Electrically floating means that there is no impressed voltage although a charge may build up due to static electricity or due to interaction with the plasma.

A preferred shape of the glow discharge electrode 204, is shown in FIG. 3a. In this embodiment, the glow discharge electrode 204 is separate from the microtextured substrate 104 and is shaped so that evaporate flow from the evaporate inlet 202 substantially flows through an electrode opening 206. Any electrode shape can be used to create the glow discharge, however, the preferred shape of the electrode 204 does not shadow the plasma from the evaporate issuing from the outlet 202 and its symmetry, relative to the polymer precursor exit slit 202 and microtextured substrate 104, provides uniformity of the evaporate vapor flow to the plasma across the width of the substrate while uniformity transverse to the width follows from the substrate motion.

The spacing of the electrode 204 from the microtextured substrate 104 is a gap or distance that permits the plasma to impinge upon the substrate. This distance that the plasma extends from the electrode will depend on the evaporate species, electrode 204/microtextured substrate 104 geometry, electrical voltage and frequency, and pressure in the standard way as described in detail in ELECTRICAL DISCHARGES IN GASES, F.M. Penning, Gordon and Breach Science Publishers, 1965, and summarized in THIN FILM PROCESSES, J.L. Vossen, W. Kern, editors, Academic Press, 1978, Part II, Chapter II-1, Glow Discharge Sputter Deposition, both hereby incorporated by reference.

An apparatus suitable for batch operation is shown in FIG. 4. In this embodiment, the glow discharge electrode 204 is sufficiently proximate a part 300 (microtextured substrate) that



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the part 300 is an extension of or part of the electrode 204. Moreover, the part is below a dew point to allow cryocondensation of the glow discharge plasma on the part 300 and thereby coat the part 300 with the polymer precursor condensate and self cure into a polymer layer.

Sufficiently proximate may be connected to, resting upon, in direct contact with, or separated by a gap or distance that permits the plasma to impinge upon the substrate. This distance that the plasma extends from the electrode will depend on the evaporate species, electrode 204/microtextured substrate 104 geometry, electrical voltage and frequency, and pressure in the standard way as described in ELECTRICAL DISCHARGES IN GASSES, F.M. Penning, Gordon and Breach Science Publishers, 1965, hereby incorporated by reference. The substrate 300 may be stationary or moving during cryocondensation. Moving includes rotation and translation and may be employed for controlling the thickness and uniformity of the polymer precursor layer cryocondensed thereon. Because the cryocondensation occurs rapidly, within milli-seconds to seconds, the part may be removed after coating and before it exceeds a coating temperature limit.

In operation, either as a method for plasma enhanced chemical vapor deposition of low vapor pressure materials (coating material) onto a microtextured surface, or as a method for making self-curing polymer layers (especially PML), the method of the invention includes flash evaporating a polymer precursor forming an evaporate, passing the evaporate to a glow discharge electrode creating a glow discharge polymer precursor plasma from the evaporate, and cryocondensing the glow discharge polymer precursor plasma on a substrate as a condensate and crosslinking the condensate thereon, the crosslinking resulting from radicals created in the glow discharge plasma.

The flash evaporating may be performed by supplying a continuous liquid flow of the polymer precursor into a vacuum environment at a temperature below both the decomposition temperature and the polymerization temperature of the polymer precursor, continuously atomizing the polymer precursor into a continuous flow of droplets, and continuously vaporizing the droplets by continuously contacting the droplets on a heated surface having a temperature at or above a boiling point of the liquid polymer precursor, but below a pyrolysis temperature,

forming the evaporate. The droplets typically range in size from about 1 micrometer to about 50 micrometers, but they could be smaller or larger.

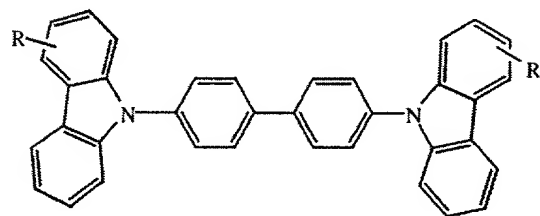
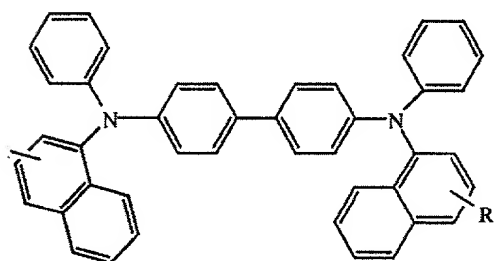
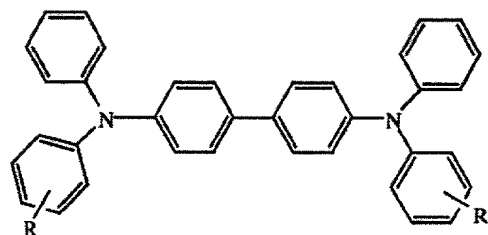
Alternatively, the flash evaporating may be performed by supplying a continuous liquid flow of the polymer precursor into a vacuum environment at a temperature below both the decomposition temperature and the polymerization temperature of the polymer precursor, and continuously directly vaporizing the liquid flow of the polymer precursor by continuously contacting the liquid polymer precursor on a heated surface having a temperature at or above the boiling point of the liquid polymer precursor, but below the pyrolysis temperature, forming the evaporate. This may be done using the vaporizer disclosed in U.S. Patent Nos. 5,402,314, 5,536,323, and 5,711,816, which are incorporated herein by reference.

The polymer precursor may be any liquid polymer precursor. However, it is preferred that the liquid polymer precursor has a low vapor pressure at ambient temperatures so that it will readily cryocondense. The vapor pressure of the liquid polymer precursor may be less than about 10 torr at 83°F (28.3°C), less than about 1 torr at 83°F (28.3°C), and less than about 10 millitorr at 83°F (28.3°C). Liquid polymer precursors include, but are not limited to, phenylacetylene (Fig. 5a), (meth)acrylates, alkenes, and alkynes, and combinations thereof.

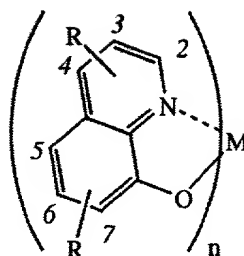
Further, to increase its functionality the liquid polymer precursor may include additional materials which may be soluble, insoluble, or partially soluble in the liquid polymer precursor. The particle(s) may be any soluble, insoluble, or partially soluble particle type having a boiling point below a temperature of the heated surface in the flash evaporation process. Soluble particles include, but are not limited to, substituted metal tris (N-R 8-quinolinolato) chelates, wherein N is between 2 and 7 and is the substituent position of the ligand, and wherein R is H, alkyl, alkoxy, and fluorinated hydrocarbons; and substituted tertiary aromatic amines; such as for example:



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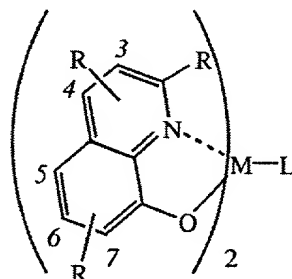
R = H, alkyl, alkoxy,
and fluorinated hydrocarbons



$n = 3, M = Al^{+3}, Ga^{+3}, In^{+3}$

$n = 1, M = Li^{+1}$

R = alkyl, alkoxy, and fluorinated
hydrocarbons



$M = Al^{+3}, Ga^{+3}, In^{+3}$

R = alkyl, alkoxy, and fluorinated
hydrocarbons

L = monodentate ligand, such as
carboxylate, phenolate and derivatives of.



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Insoluble particles include, but are not limited to, tertiary aromatic amines such as, triphenyl diamine derivatives (TPD, FIG. 5b), quinacridone derivatives (QA, FIG. 5c), and metal (8-quinolinolato) chelates, such as aluminum quinolinolato, (Alq), gallium quinolinolato (Gaq), and lithium quinolinolato (Liq), and combinations thereof. Partially soluble means that some of the particles do not dissolve in the polymer precursor, including the situation in which a soluble particle is present in a concentration exceeding the solubility limit in the polymer precursor so that some of the dissolvable material remains undissolved.

The particles generally have a volume much less than about 5000 cubic micrometers (diameter about 21 micrometers) or equal thereto, typically less than or equal to about 4 cubic micrometers (diameter about 2 micrometers). The insoluble particles may be sufficiently small with respect to particle density and liquid polymer precursor density and viscosity that the settling rate of the particles within the liquid polymer precursor is several times greater than the amount of time to transport a portion of the particle liquid polymer precursor mixture from a reservoir to the atomization nozzle. It may be necessary to agitate the particle liquid polymer precursor mixture in the reservoir to maintain suspension of the particles and avoid settling. As used herein, agitation includes, but is not limited to, stirring, physical shaking, ultrasonic vibration, and convection (thermal gradient).

The mixture of polymer precursor and soluble, insoluble, or partially soluble particles may be considered a solution, slurry, suspension or emulsion, and the particles may be solid or liquid. The mixture may be obtained by several methods. One method is to mix insoluble particles of a specified size into the polymer precursor. The insoluble particles of a solid of a specified size may be obtained by direct purchase or by making them by one of any standard techniques, including, but not limited to, milling from large particles, precipitation from solution, melting/spraying under controlled atmospheres, rapid thermal decomposition of precursors from solution as described in U.S. Patent No. 5,652,192 hereby incorporated by reference. The steps of U.S. Patent No. 5,652,192 are making a solution of a soluble precursor in a solvent and flowing the solution through a reaction vessel, pressurizing and heating the flowing solution and forming substantially insoluble particles, then quenching the heated flowing solution and



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arresting growth of the particles. Alternatively, larger sizes of solid material may be mixed into liquid polymer precursor then agitated, for example ultrasonically, to break the solid material into particles of sufficient size.

Liquid particles may be obtained by mixing an immiscible liquid with the polymer precursor liquid and agitating by ultrasonic or mechanical mixing to produce liquid particles within the liquid polymer precursor. Immiscible liquids include, for example, phenylacetylene.

If an atomizer is used, upon spraying, the droplets may be particles alone, particles surrounded by liquid polymer precursor, and liquid polymer precursor alone. Since both the liquid polymer precursor and the particles are evaporated, it is of no consequence either way. The droplets should be sufficiently small that they are completely vaporized. The droplet size typically ranges from about 1 micrometer to about 50 micrometers, although the particles may be larger or smaller.

By using flash evaporation, the coating material polymer precursor is vaporized so quickly that reactions that generally occur from heating a liquid material to an evaporation temperature simply do not occur. Further, control of the rate of evaporate delivery is strictly controlled by the rate of material delivery to the inlet 118 of the flash evaporator 106.

In addition to the evaporate from the polymer precursor, additional gases may be added within the flash evaporator 106 through a gas inlet 130 upstream of the evaporate outlet 128, preferably between the heated surface 124 and the first baffle 126 nearest the heated surface 124. Additional gases may be organic or inorganic for purposes including, but not limited to, ballast, reaction, and combinations thereof. Ballast refers to providing sufficient molecules to keep the plasma lit in circumstances of low evaporate flow rate. Reaction refers to chemical reaction to form a compound different from the evaporate. Additional gases include but are not limited to group VIII of the periodic table, hydrogen, oxygen, nitrogen, chlorine, bromine, polyatomic gases including for example carbon dioxide, carbon monoxide, water vapor, and combinations thereof.

The method of the present invention is insensitive to a direction of motion of the substrate because the deposited polymer precursor layer is self curing. Also, the conjugation (if any) is preserved during curing. In addition, multiple layers of materials may be combined. For

